

# VERTICAL FIELD EFFECT TRANSISTORS HAVING IMPROVED BREAKDOWN VOLTAGE CAPABILITY AND LOW ON- STATE RESISTANCE

## FIELD OF THE INVENTION

The present invention relates to semiconductor switching devices, and more particularly to switching devices for high power applications.

## BACKGROUND OF THE INVENTION

The silicon bipolar transistor has been the device of choice for high power applications in motor drive circuits, appliance controls, robotics and lighting ballasts. This is because bipolar transistors can be designed to handle relatively large current densities in the range of 40–50 A/cm<sup>2</sup> and support relatively high blocking voltages in the range of 500–1000 V.

Despite the attractive power ratings achieved by bipolar transistors, there exist several fundamental drawbacks to their suitability for all high power applications. First of all, bipolar transistors are current controlled devices which require relatively large base currents, typically one fifth to one tenth of the collector current, to maintain the transistor in an operating mode. Proportionally larger base currents can be expected for applications which also require high speed turn-off. Because of the large base current demands, the base drive circuitry for controlling turn-on and turn-off is relatively complex and expensive. Bipolar transistors are also vulnerable to premature breakdown if a high current and high voltage are simultaneously applied to the device, as commonly required in inductive power circuit applications. Furthermore, it is relatively difficult to operate bipolar transistors in parallel because current diversion to a single transistor typically occurs at high temperatures, making emitter ballasting schemes necessary.

The silicon power MOSFET was developed to address this base drive problem. In a power MOSFET, the gate electrode provides turn-on and turn-off control upon the application of an appropriate gate bias. For example, turn-on in an N-type enhancement MOSFET occurs when a conductive N-type inversion layer is formed in the P-type channel region in response to the application of a positive gate bias. The inversion layer electrically connects the N-type source and drain regions and allows for majority carrier conduction therebetween.

The power MOSFET's gate electrode is separated from the channel region by an intervening insulating layer, typically silicon dioxide. Because the gate is insulated from the channel region, little if any gate current is required to maintain the MOSFET in a conductive state or to switch the MOSFET from an on-state to an off-state or vice-versa. The gate current is kept small during switching because the gate forms a capacitor with the MOSFET's channel region. Thus, only charging and discharging current ("displacement current") is required during switching. Because of the high input impedance associated with the insulated-gate electrode, minimal current demands are placed on the gate and the gate drive circuitry can be easily implemented. Moreover, because current conduction in the MOSFET occurs through majority carrier transport only, the delay associated with the recombination and storage of excess minority carriers is not present. Accordingly, the switching speed of power MOSFETs can be made orders of magnitude faster than that of bipolar transistors. Unlike bipolar transistors, power MOSFETs can be designed to withstand

high current densities and the application of high voltages for relatively long durations, without encountering the destructive failure mechanism known as "second breakdown". Power MOSFETs can also be easily paralleled, because the forward voltage drop of power MOSFETs increases with increasing temperature, thereby promoting an even current distribution in parallel connected devices.

In view of these desirable characteristics, many variations of power MOSFETs have been designed. Two popular types are the double-diffused MOSFET device (DMOSFET) and the UMOSFET device. These and other power MOSFETs are described in a textbook by B. J. Baliga entitled *Power Semiconductor Devices*, PWS Publishing Co. (ISBN 0-534-94098-6) (1995), the disclosure of which is hereby incorporated herein by reference. Chapter 7 of this textbook describes power MOSFETs at pages 335–425. Examples of silicon power MOSFETs including accumulation, inversion and extended trench FETs having trench gate electrodes extending into the N+ drain region are also disclosed in an article by T. Syau, P. Venkatraman and B. J. Baliga, entitled *Comparison of Ultralow Specific On-Resistance UMOSFET Structures: The ACCUFET, EXT-FET, INVFET, and Conventional UMOSFETs*, IEEE Transactions on Electron Devices, Vol. 41, No. 5, May (1994). As described by Syau et al., specific on-resistances in the range of 100–250  $\mu\Omega\text{cm}^2$  were experimentally demonstrated for devices capable of supporting a maximum of 25 volts. However, the performance of these devices was limited by the fact that the forward voltage was supported across the gate oxide at the bottom of the trench instead of the semiconductor substrate.

FIG. 1, which is a reproduction of FIG. 1(d) from the aforementioned Syau et al. article, discloses a conventional UMOSFET structure. In the blocking mode of operation, this UMOSFET supports most of the forward voltage across the N- drift layer which can be doped at relatively low levels to obtain a high maximum blocking voltage capability, however low doping levels typically increase the on-state series resistance. Based on these competing design requirements of high blocking voltage and low on-state resistance, a fundamental figure of merit for power devices has been derived which relates specific on-resistance ( $R_{on,sp}$ ) to the maximum blocking voltage (BV). As explained at page 373 of the aforementioned textbook to B. J. Baliga, the ideal specific on-resistance for an N-type silicon drift region is given by the following relation:

$$R_{on,sp} = 5.93 \times 10^{-9} (BV)^{2.5}$$

Thus, for a device with 60 volt blocking capability, the ideal specific on-resistance is 170  $\mu\Omega\text{cm}^2$ . However, because of the additional resistance contribution from the channel region (P base), reported specific on-resistances for UMOSFETs are typically much higher. For example, a UMOSFET having a specific on-resistance of 730  $\mu\Omega\text{cm}^2$  is disclosed in an article by H. Chang, entitled *Numerical and Experimental Comparison of 60V Vertical Double-Diffused MOSFETs and MOSFETs With A Trench-Gate Structure*, Solid-State Electronics, Vol. 32, No. 3, pp. 247–251, (1989). However, in this device a lower-than-ideal uniform doping concentration in the drift region was required to compensate for the high concentration of field lines near the bottom corner of the trench when blocking high forward voltages.

Thus, notwithstanding these attempts to develop power MOSFETs with high maximum blocking voltage capability and low specific on-resistance, there still continues to be a need to develop improved power MOSFETs which are